APPENDIX G

SEISMIC REPORT

CALFED
BAY-DELTA
PROGRAM

Levees and Channels Technical Team
Seismic Vulnerability Sub-Team

Seismic Vulnerability of the Sacramento - San Joaquin Delta Levees

April 2000

Seismic Vulnerability of the Sacramento - San Joaquin Delta Levees

Levees and Channels Technical Team
Seismic Vulnerability Sub-Team
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CALFED BAY-DELTA PROGRAM
SEISMIC VULNERABILITY
OF THE
SACRAMENTO/SAN JOAQUIN DELTA LEVEES

FORWORD

The CALFED Bay-Delta program is an unprecedented collaboration among state and federal agencies and the state's leading urban, agricultural and environmental interests to address and resolve the environmental and water management problems associated with the Bay-Delta system. The mission of the CALFED Bay-Delta Program is to develop a long-term comprehensive plan that will restore ecological health and improve water management for beneficial uses of the Bay-Delta system. The objective of CALFED's Levee System Integrity Program is to reduce the risk to land use and associated economic activities, water supply, infrastructure, and the ecosystem from catastrophic damage associated with breaching of Delta levees.

Delta levees are the most visible man-made feature of the Bay-Delta system. They are an integral part of the Delta landscape and are key to preserving the Delta's physical characteristics and processes, including definition of the Delta waterways and islands. There is concern that California's Bay-Delta system levees are vulnerable to failure, especially during earthquakes. Levee failures in the Delta could flood farmland and wildlife habitat, and also interrupt water supply deliveries to urban and agricultural users and disrupt highway and rail use. Although there has never been a documented levee failure from a seismic event, the Delta has not experienced a significant seismic event since the levees have been at their current size. One goal of CALFED's Levee Program is to identify the risk of failure of Delta levees due to seismic events and develop recommendations to reduce levee vulnerability and improve levee seismic stability.

A Seismic Vulnerability Sub-Team of CALFED's Levees and Channels Technical Team was formed to assess the seismic risk. This sub-team, composed of seismic experts and geotechnical engineers with experience in the Delta, evaluated levee fragility and assessed the seismic vulnerability of the current levee system. This report presents the findings and conclusions of the Seismic Sub-Team. CALFED's Levee Program will conduct further studies to apply this information to overall risk assessment.

CALFED thanks DWR's Division of Engineering for sponsoring this exceptional study and also recognizes the superior efforts of the experts on the sub-team who contributed their unique technical knowledge, diverse views, and willingness to work long hours.

CALFED BAY-DELTA PROGRAM SEISMIC VULNERABILITY OF THE SACRAMENTO/SAN JOAQUIN DELTA LEVEES EXECUTIVE SUMMARY

The objective of CALFED's Levee System Integrity Program is to reduce the risk to land use and associated economic activities, water supply, infrastructure, and the ecosystem from catastrophic damage associated with breaching of California's Bay-Delta system levees. Delta levees are at risk from many sources of failure, including stability, seepage, overtopping, erosion, unseen defects, and seismic. This report only addresses the seismic risk.

Although there has never been a documented levee failure from a seismic event, the Delta has not experienced a significant seismic event since the levees have been at their current size. A team composed of seismic experts and geotechnical engineers with experience in the Delta assessed the seismic risk.

This report provides an assessment of the Delta levees' current vulnerability to potential damage caused by an earthquake. These seismic risk analyses and assessments are based on the most current available information. It is not likely that additional information in the near future would significantly change the present characterization. This assessment also provides an estimate of the probability or likelihood that a damaging earthquake will occur.

This study subdivided the Delta into four Damage Potential Zones. Seismic vulnerability is highest in Zone I, Sherman Island, due to poor levee embankment and foundation soils, and higher exposure to seismic shaking at the western edge of the Delta. Zone II, the central area of the Delta, has the next highest overall level of seismic levee fragility and exposure to seismic shaking. Zones III and IV, with levees of lower heights more distant from earthquake shaking, have generally lower levels of seismic vulnerability.

The final, overall estimate of potential levee failures during a single seismic event is shown in Figure 5-2 on page 23. This figure shows, for example, that an earthquake with a 100-year return period is predicted to cause 3 to 10 levee failures in the Delta, on one or more islands.

While this report quantifies the magnitude of the current seismic vulnerability of Delta levees, CALFED continues to investigate the overall risk. Two teams have been formed. One team of geotechnical engineers is developing recommendations for seismic upgrades and other measures to reduce levee failures. Another team will perform an overall risk assessment of multiple factors that contribute to levee failure, evaluate the consequences of failure, and develop risk management options. Once these two studies are completed, the level of seismic risk in relation to the total risk to Delta levees will be better understood.

CALFED staff will work with stakeholders, the public, and state and federal agencies to develop and implement a Delta levee risk assessment and risk management strategy. CALFED will incorporate the findings from the Geotechnical and Risk Assessment Subteams into an overall risk assessment. Once the risk to Delta levees is quantified and the consequences evaluated, CALFED will develop and implement an appropriate risk management strategy.

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1 INTRODUCTION

1.1 BACKGROUND

The CALFED process has produced a draft programmatic environmental impact report that describes three alternatives for improving the Delta's levees, environment, water quality, and water supply reliability. The seismic risk assessment described in this report provides an assessment of the Delta's levees current vulnerability to potential damage caused by an earthquake. This assessment also provides an estimate of the probability or likelihood that a damaging earthquake will occur. This information will be used to evaluate the CALFED alternatives with respect to the seismic impact to the Delta.

1.2 ORGANIZATION

This seismic risk assessment was performed by a sub-team of the Levees and Channels Technical Team of CALFED. The sub-team is comprised of geotechnical engineers and a seismologist. The members represent Federal and State government, local interests, and independent consultants. The members of the sub-team are:

Dr. Norman A. Abrahamson	Consulting Seismologist
Fred N. Brovold	GEI Consultants
Gilbert Cosio	Murray, Burns, and Kienlen, Consulting Engineers
Michael W. Driller	Department of Water Resources
Dr. Leslie F. Harder, Jr.	Department of Water Resources
Dr. N. Dean Marachi	The Mark Group, Consulting Engineers
Christopher H. Neudeck	Kjeldsen, Sinnock, Neudeck, Consulting Engineers
Lynn Moquette O'Leary	CALFED/U.S. Army Corps of Engineers
Michael Ramsbotham	CALFED/U.S. Army Corps of Engineers
Dr. Raymond B. Seed	Seismic Geotechnical Consultant
Raphael A. Torres - Chair	Department of Water Resources

1.3 BASIS FOR THE ASSESSMENTS

The seismic risk analyses and assessments presented in this report are based on the most current available information. Information on the seismic response of peat/organic soils is still being developed. Even though hundreds of borings describing the subsurface conditions of Delta levees were reviewed, these borings can only provide a limited characterization of the hundreds of miles of levees. Yet, it is not likely that a finite number of additional borings would significantly change the present characterization.

Additional investigations cannot be completed within the CALFED time frame. Consequently, a combination of sensitivity analyses and assumptions were used to fill this information void. The sub-team determined that even though there was little information available on some issues, a reasonable assessment of the Delta as a whole could still be achieved. This is described in more detail in the report.

Members of the Seismic Vulnerability Sub-Team:
Top Row, Left to Right: Michael W. Driller, Dr. Raymond B. Seed, Frederick N. Brovold, Dr. Leslie F. Harder, Jr., Dr. Norman A. Abrahamson, Michael Ramsbotham
Bottom Row, Left to Right: Christopher H. Neudeck, Gilbert Cosio, Dr. N. Dean Marachi, Lynn Moquette O'Leary, Raphael A. Torres

2 GEOLOGIC SETTING

2.1 GEOLOGY

The Sacramento-San Joaquin Delta, located at the confluence of the Sacramento and San Joaquin Rivers, is a unique feature of the California landscape (see Figure 2-1). The Delta is part of the Central Valley geomorphic province, a northwest-trending structural basin separating the primarily granitic rock of the Sierra Nevada from the primarily Franciscan Formation rock of the California Coastal Ranges (Converse et al., 1981). The Delta occurs in an area that contains 3 to 6 mile thick/deep sedimentary deposits, most of which accumulated in a marine environment from about 175 million years ago to 25 million years ago.

Since late Quaternary time, the Delta area has undergone several cycles of deposition, non-deposition, and erosion, resulting in the accumulation of a few hundred feet of poorly consolidated to unconsolidated sediments. Delta peats and organic soils began to form about 11,000 years ago during a rise in sea levels (Shlemon and Begg, 1975). This rise in sea level created tule marshes that covered most of the Delta. Peat formed from repeated burial of the tules and other vegetation growing in the marshes.

During the cycles of erosion and deposition, rivers were entering from the north, northeast, and southeast. These included the Sacramento, Mokelumne, and San Joaquin Rivers. As the rivers merged, they formed a complex pattern of islands and interconnecting sloughs. River and slough channels were repeatedly incised and backfilled with sediments with each major fluctuation. These processes were complicated by concurrent subsidence and tectonic changes in the land surface.

Debris produced by hydraulic mining during the gold rush of the mid-1800's disrupted the natural depositional history of the Delta. Hundreds of thousands of tons of silt, sand, and gravel were washed from the Sierra Nevada into the Delta. This sediment filled stream channels, caused flooding, and raised the natural levees along Delta streams and sloughs.

2.2 LEVEE BUILDING HISTORY

In the late 1800's, Delta inhabitants began fortifying existing natural levees and draining inundated islands in the Delta for agricultural use.

Most of the early levees in the Delta were constructed by Chinese laborers (Thompson, 1982) using hand shovels and wheelbarrows, and some were built using scrapers pulled by horses. Later, when the farmers realized that levees of sufficient height could not be efficiently built by hand, the barge-mounted, sidedraft-clamshell dredge was used. The levees were generally built of non-select, uncompacted materials without engineering design and without good construction methods.

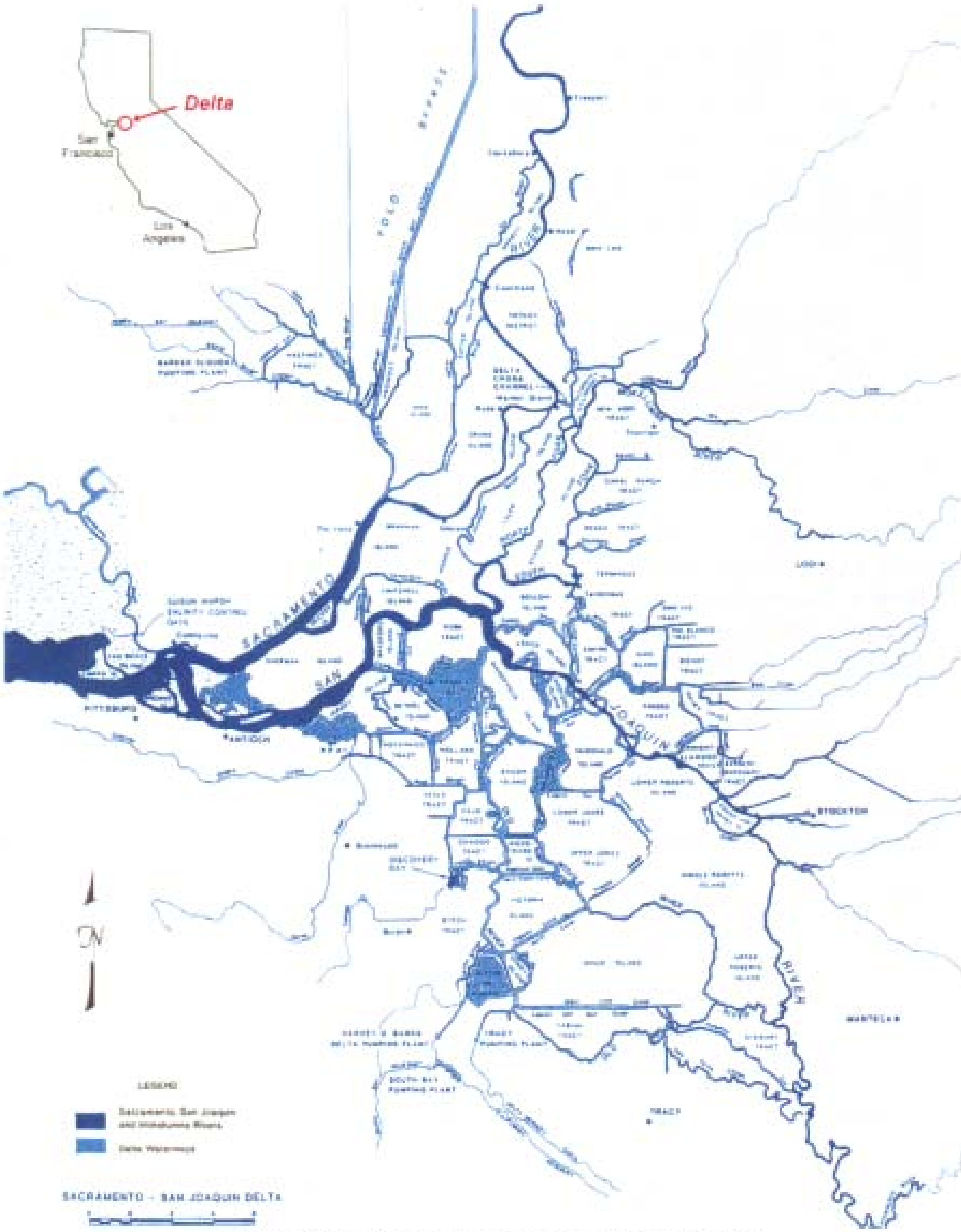

Figure 2-1: Sacramento - San Joaquin Delta

The original levees were usually less than five feet high, but continuous settlement of the levees and subsidence of near levee soils has required the periodic addition of new fill to maintain protection against overtopping by waters of the Delta. The interiors of many islands are now commonly 10 to 15 feet below sea level. Presently, some levee crowns are 25 feet higher than the interior of their respective islands. Figure 2-2 illustrates the evolution of Delta levees over time.

In general, the upper portion of Delta levee embankments are comprised of mixtures of dredged organic and inorganic sandy, silty, or clayey soils that have been placed on either natural peat or natural sand and silt levees. The variability in foundation materials for Delta levees can be great, even between sites that are in close proximity to one another. Such heterogeneity is due to a history of continuous stream meandering and channel migration within the Delta.

2.3 LEVEE DAMAGE CAUSED BY PAST EARTHQUAKES

Historical information indicates that there has been little damage to Delta levees caused by earthquakes (CDWR, 1992). No reports could be found to indicate that an island or tract had been flooded due to an earthquake-induced levee failure. Further, no report could be found to indicate that significant damage had ever been induced by earthquake shaking. The minor damage that has been reported has not significantly jeopardized the stability of the Delta levee system.

This lack of severe earthquake-induced levee damage corresponds to the fact that no significant earthquake motion has apparently ever been sustained in the Delta area since the construction of the levee system approximately a century ago. The 1906 San Francisco earthquake occurred 50 miles to the west, on the San Andreas Fault, and produced only minor levels of shaking in the Delta; as the levees were not very tall yet in 1906, these shaking levels posed little threat. Continued settlement and subsidence over the past 90 years has, however, significantly changed this situation. Consequently, the lack of historic damage to date should not lead, necessarily, to a conclusion that the levee system is not vulnerable to moderate-to-strong earthquake shaking. The current levee system simply has never been significantly tested.

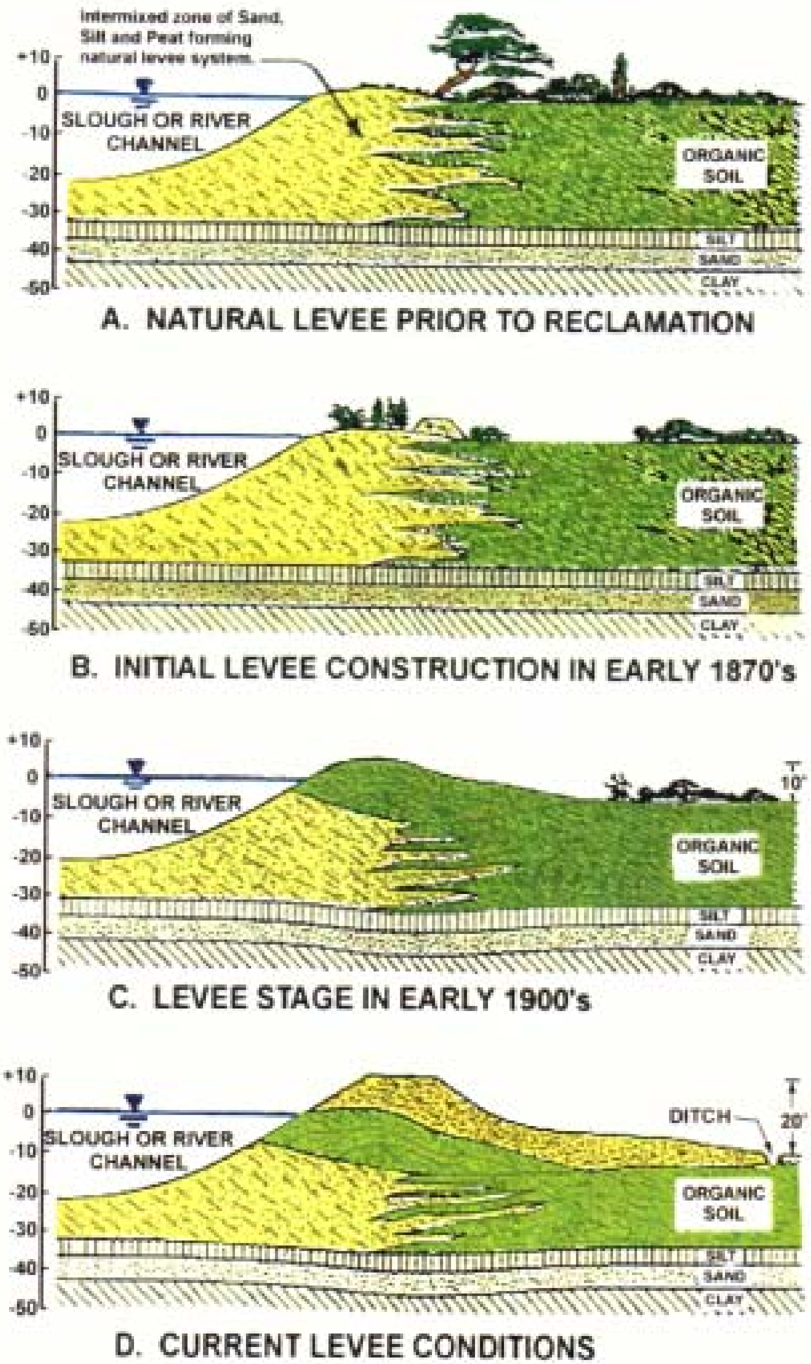

Figure 2-2: Evolution of Delta Levees Over Time

3.0 SEISMICITY OF THE DELTA REGION

3.1 REGIONAL FAULTING AND MODELS

The Delta Levees are located in a region of relatively low seismic activity as compared to the San Francisco Bay area. The major strike-slip faults in the Bay Area (San Andreas, Hayward, Calaveras faults) are located over 16 miles from the Delta region (see Figure 3-1). The less active Green Valley and Marsh Creek-Clayton faults are over 9 miles from the Delta region. There are also small but significant local faults in the Delta region, and there is a possibility that there are blind thrust faults along the western Delta (see Figures 3-1 and 3-2).

3.2 LOCAL FAULTING AND MODELS

In recent seismic studies of the Delta region, a series of blind thrust faults along the western edge of the Central Valley and extending through the Delta has typically been used in the seismic source characterization. However, there is large uncertainty in the location, activity, and even existence of these blind thrust faults in the Delta region. Although various names have been used for this theoretical system of blind thrust faults, in this study we have used the term Coast-Range Central Valley (CRCV) boundary thrust fault system. While there is clear evidence that the CRCV fault system exists and is potentially active to the south and north of the Delta, there is not clear evidence of potentially active blind thrust faults in the Delta region. The possibility that the CRCV fault system exists in the Delta region has a significant effect on the seismic risk to the Delta levees. Due to the large uncertainty in this important aspect of the source characterization, two alternative models of the local faulting have been used in this study: One that includes the CRCV feature in the Delta region, and an alternate one that includes smaller thrust faults west of the Delta region.

The first model is based on the seismic source characterization currently used by the California Division of Mines and Geology (1996) which are part of the state seismic hazard map. In this model, the CRCV is assumed to extend into the Delta region (see Figure 3-1). This model is called the "CRCV" model in this study.

The second model is based on a recent evaluation of the faulting in the Delta region by (Lettis and Associates 1998). This study has concluded that the blind thrust faults do not exist in the Delta region. Instead, thrust faults located further west of the Delta region are postulated as accounting for the crustal shortening across the region (see Figure 3-2). This model is called the "without-CRCV," or "Lettis," model in this study.

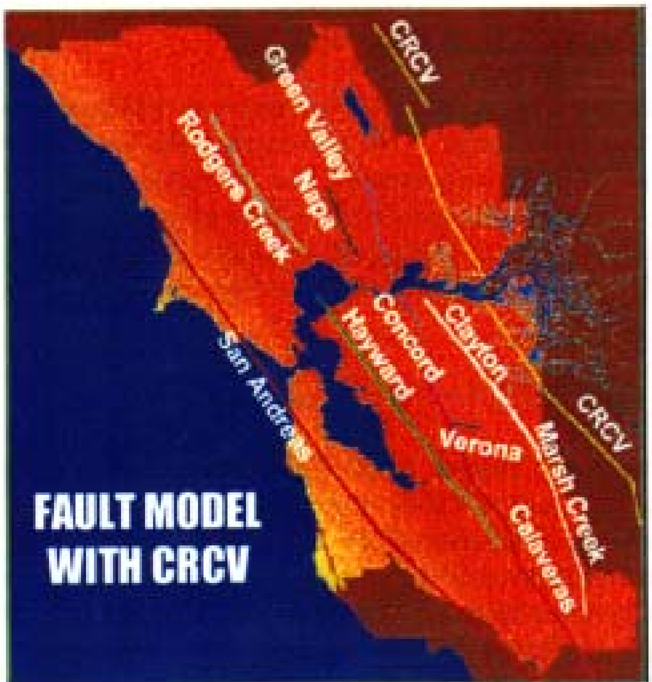

Figure 3-1: Delta Fault Model With CRCV

Figure 3-2: Delta Fault Model Without CRCV

3.3 SEISMIC HAZARD RESULTS

Although the two local faulting models are quite different, they produce similar levels of peak ground acceleration (PGA) at individual sites in the Delta region using a probabilistic analysis. For an outcrop of stiff soil or rock, the 100-year PGA ranges from 0.2g in the western Delta to 0.1g along the northeastern Delta (see Figure 3-3). Figure 3-4 presents the estimated PGA at Sherman Island for a range of return periods. Once again, both the "with CRCV" and "without CRCV" models produce similar predictions of PGA. However, while the individual site PGA is similar for the two models, the magnitudes associated with them are different and this leads to very different predictions of performance of the Delta as a system which is discussed later.

For the western Delta, the dominant earthquake contributing to the 100-year PGA is a magnitude 5.8 to 6.2 earthquake at a distance of about 13 miles from local sources. For the eastern Delta, earthquakes with magnitudes of 7 or higher on the more distant San Andreas and Hayward Faults also contribute significantly to the hazard. However, the main magnitude contributing to the 100-year return period hazard for the eastern Delta is also about magnitude 6.

Since the overall seismic hazard is dominated by moderate local events, it is unlikely that the entire Delta region will be subjected to large motions in any single earthquake. For example, a magnitude 6 event near the northern Delta may cause significant ground motions in the northern Delta, but not in the southern Delta, as peak accelerations produced by events of only moderate magnitude attenuate fairly rapidly with distance from the source (fault rupture).

Appendix A presents additional information regarding the seismic source models of the Delta region and the results of the probabilistic hazard analysis.

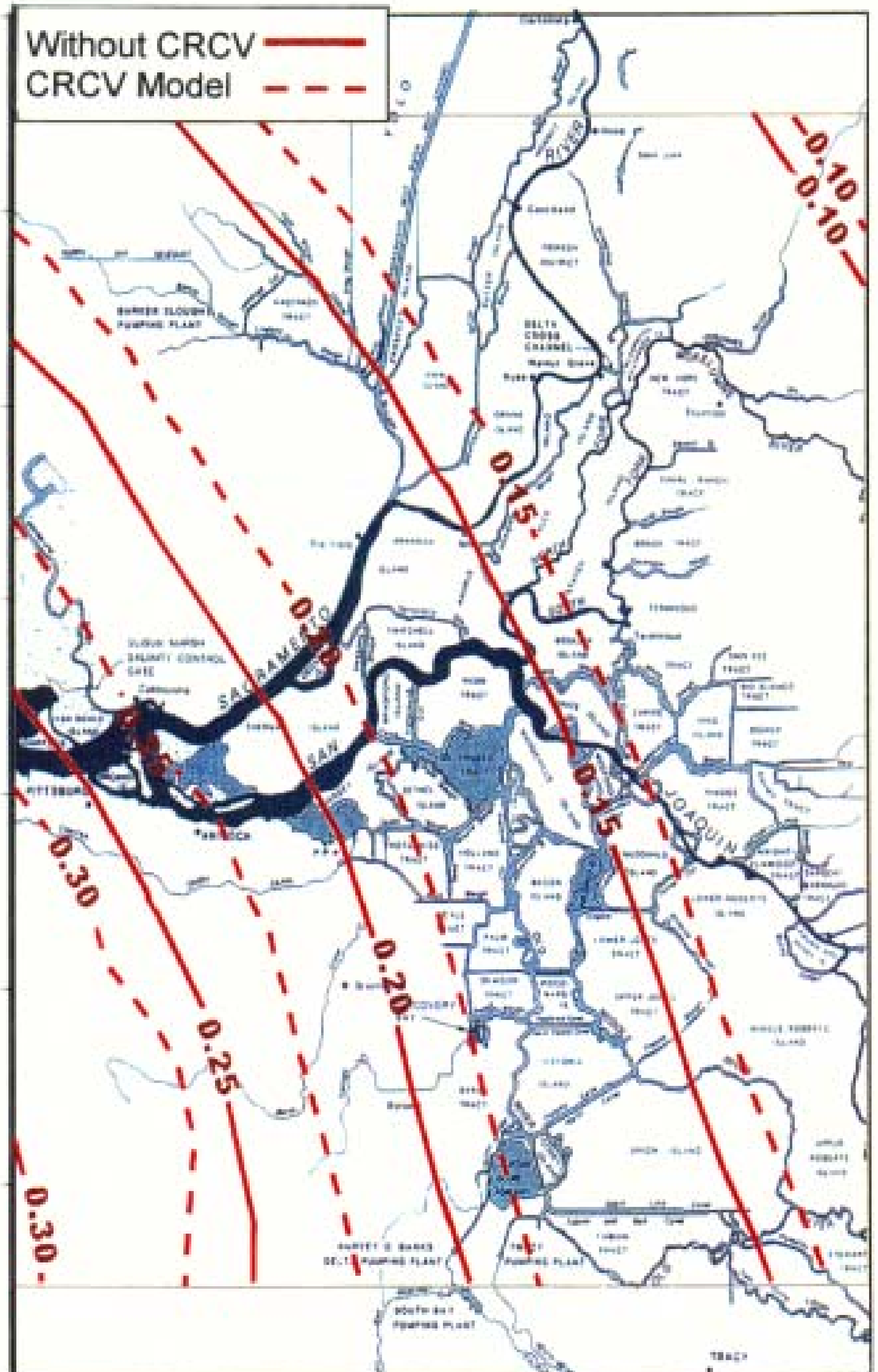

Figure 3-3: Peak Ground Acceleration (g) Contours for 100-year Return Interval – both Models

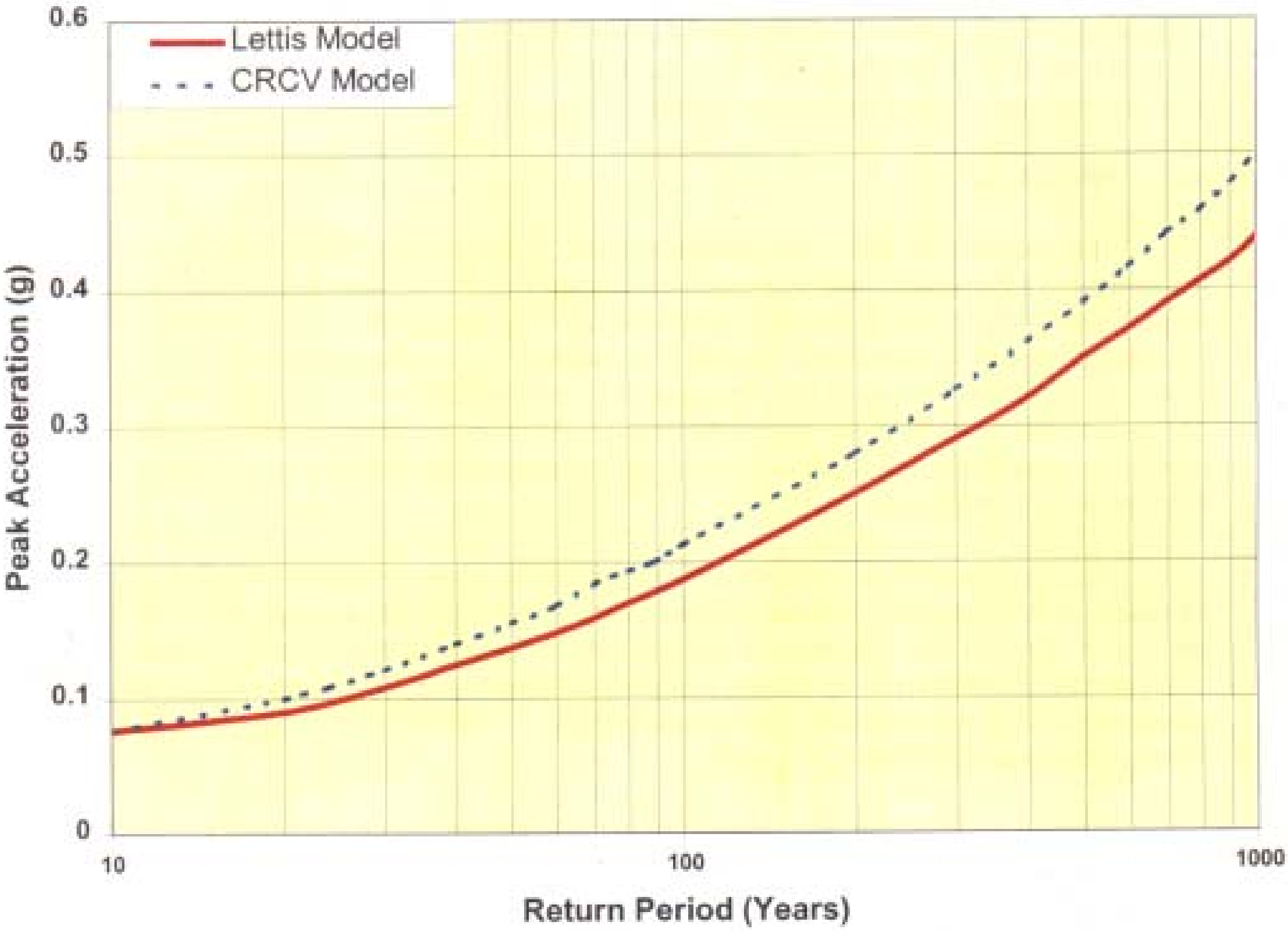

Figure 3-4: Peak Ground Acceleration vs. Return Period for the CRCV and Lettis Models at Sherman Island

4 ESTIMATES OF LEVEE FRAGILITY DUE TO EARTHQUAKE SHAKING

4.1 INTRODUCTION

Levee fragility is defined as a measure of the susceptibility of a levee to fail due to seismic loading. Available geotechnical information and previous seismic stability studies associated with levees in the Delta were used to assess the relative vulnerability of the levees and their foundations to earthquake shaking. Geotechnical reports and data were supplied by the California Department of Water Resources, U. S. Army Corps of Engineers, Kjeldsen Sinnock & Neudeck, and Murray Burns & Kienlen. Appendix E presents a list of some of the reports and studies reviewed.

4.2 PROCESS

The process for assessing potential levee failures during earthquakes was to review the available information and to develop a range of estimates for the number of levee failures that might occur for various levels of earthquake acceleration. This levee fragility was expressed in a normalized form as the number of expected levee failures per 100 miles of levee. Different ranges of fragility were estimated for different regions in the Delta, and for different levels of earthquake shaking. This information is used in a later section, together with the probabilistic seismicity estimates, to develop estimates of the number of failures likely within an exposure period.

Failure was defined as sufficient distress to the levee in the form of lateral spreading, slumping and/or cracking that would lead to a complete breach and uncontrolled flooding of the island. Failure was considered to occur either during the earthquake, or within a very short period of time following the earthquake. Levees could be extensively damaged during or subsequent to earthquake shaking, but unless a full breach of the levee resulted, failure was not considered to have occurred.

Precise quantitative estimates of levee failures cannot be made because geotechnical information for over 600 miles of levees remains limited, particularly for the levees themselves. The sub-team members relied upon the available information and their individual knowledge and experience to develop individual assessments of the frequencies of levee failure for different levels of earthquake shaking. These individual assessments were then discussed by the sub-team and refined into a single consensus range of values.

4.3 EARTHQUAKE MOTIONS CONSIDERED

The likely range of bedrock/stiff soil accelerations that might be experienced on an outcrop of such materials within the Delta within the next 30 to 300 years is between 0.05

and 0.30g (see Section 3). Such motions are expected to be generally associated with a Magnitude 6 event. However, the Delta has thick and deep deposits of soft organic and mineral soils overlying the top of stiff soils. Layers of soft soils overlying stiffer deposits are generally expected to amplify earthquake motions developed in the deeper, stiffer deposits. Based on the studies by CDWR (1992) and Boulanger, et al. (1997), the most likely acceleration amplification factors from deep and stiff base layers to the levee crowns range between 1 and 2. For the purposes of the current assessments, an average amplification factor of 1.6 was used. This crown amplification accounted for both soft soil amplification as well as topographic amplification. Accordingly, the earthquake parameters considered in these fragility assessments can be summarized as follows:

Earthquake Magnitude: 6.
Peak Bedrock/Stiff Soil Outcrop Accelerations: 0.05 to 0.30g.
Base Layer to Levee Crown Amplification Factor: 1.6.

Magnitude scaling factors to adjust acceleration levels for earthquakes having magnitudes other than Magnitude 6 were incorporated in the probabilistic seismicity analyses (see Appendix B). These scaling factors account for the fact that larger magnitude events typically cause longer durations of stronger shaking, and these duration differences affect the severity of the loading.

4.4 DAMAGE POTENTIAL ZONES

Qualitative assessments of high, medium, and low failure potential during earthquake shaking were made for different regions within the Delta. The principal geotechnical parameters affecting this assessment included the following:

- The presence of loose, cohesionless sandy and silty layers in the levee embankment generally lead to a high or medium-high failure potential rating. Such soils are liquefiable when saturated. Since levees are manmade and not formed by intermittent natural processes, loose soils are expected to have greater lateral continuity within a levee than in a natural deposit. The presence of such soil beneath the phreatic line within the manmade levee embankment, as detected by penetration testing, indicates a relatively high potential for a liquefaction-induced levee failure. Levees with substantial amounts of liquefied material are likely to exhibit flow slides and lateral spreading as very loose, cohesionless soils have low post-liquefaction shear strengths.

- The presence of loose, cohesionless sandy and silty layers in the levee foundation was also considered detrimental because of the potential for liquefaction. However, it was not considered as serious as having such materials within the levee. This is because such layers within the natural foundation are more likely to be discontinuous. Foundation liquefaction beneath a levee is also generally less critical than liquefaction within the levee embankment as the post-liquefaction shear resistance necessary to prevent flow and lateral spreading is lower due to geometry and net driving force considerations. In addition, somewhat higher penetration resistance is commonly reported for such foundation layers and this suggests somewhat higher liquefaction resistance and post-liquefaction shear strength.

- High levees on thick, soft foundations were considered more fragile because of their potential to have marginal static stability. Levee sections with only marginal static stability were considered to be likely to slide and experience significant displacements during earthquake shaking even without liquefaction.

- Levees with narrow cross sections, limited freeboard, or histories of previous distress were also considered to have a higher probability of failure.

Two principal modes of potential earthquake-induced levee failure were considered while developing the different damage potential zones: 1) Flow slides and lateral spreading associated with strength loss (liquefaction) of levee embankment or foundation soils, and 2) Inertially-induced seismic deformations of levees experiencing no liquefaction. Potential failure mechanisms included overtopping, seepage erosion due to cracking, and exacerbation of existing seepage problems due to deformations and cracking. Seasonal variations in river and slough water elevations, and their interactions with tides, were also considered. This evaluation resulted in dividing the Delta area into four Damage Potential Zones as described in Table 4-1 and shown in Figure 4-1.

TABLE 4-1: DAMAGE POTENTIAL ZONES WITHIN THE DELTA

Damage Potential Zone	Levee Length in Zone (miles)	Description
I	20	**High susceptibility** to earthquake-induced levee failure. This zone encompasses only Sherman Island and was considered to have high potential for failure due to the presence of substantial liquefiable soils within the non-project levees, especially those along the San Joaquin River. These levee reaches have an unusually high amount of cohesionless sandy and silty soils within the levee section, are relatively narrow, are founded on thick deposits of soft soil, and have a history of distress.
II	301	**Medium to medium-high susceptibility** to earthquake-induced levee failure. This zone is within the central Delta and generally includes levees with high sections founded on thick deposits of soft soil. Most of the levees which have had histories of distress or that have failed during flood events are located within this zone. Vulnerability varies significantly within this region, even along adjacent levee reaches, principally as a function of the presence or absence of liquefiable soils at the base of the levee embankment sections.
III	116	**Low to medium susceptibility** to earthquake-induced levee failure. This zone is located on the southern and western periphery of the Delta and generally involves levees of smaller heights founded on thinner layers of soft soil.
IV	223	**Low susceptibility** to earthquake-induced levee failure. This zone is located on the northern and eastern periphery of the Delta and generally involves levees of smaller heights founded on thinner layers of soft soil.
TOTAL LENGTH	660 miles	

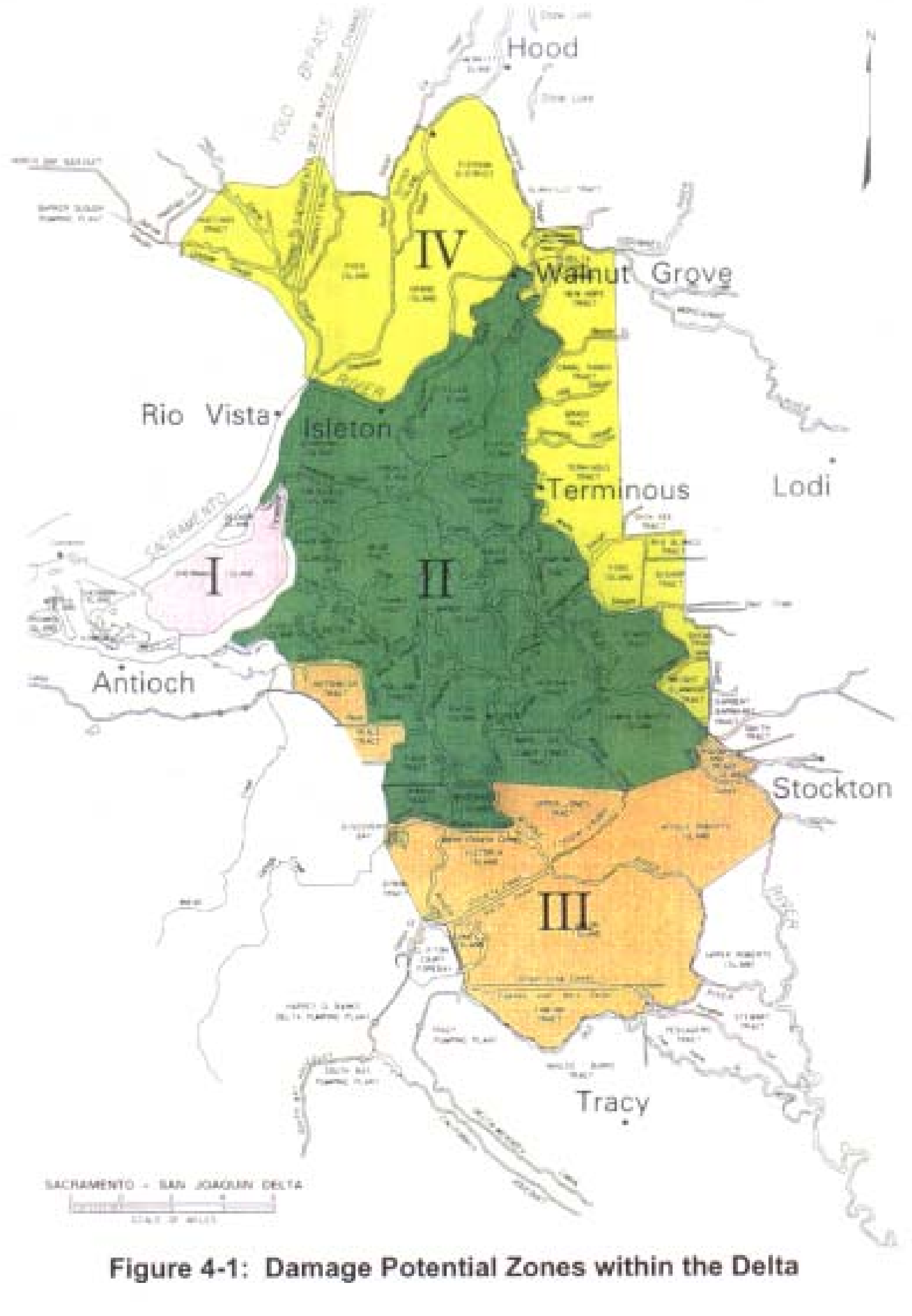

Figure 4-1: Damage Potential Zones within the Delta

4.5 ESTIMATES OF LIQUEFACTION-INDUCED LEVEE FAILURES

Liquefaction fragility estimates (failures per 100 miles of levee) were developed for different earthquake loadings based on the sub-team's experience with the performance of similar earth structures. The three principal steps in developing these estimates were as follows:

1. Levee geometries and geotechnical data from over 34 sites within the Delta were reviewed and evaluated. Each site was a levee reach (or length), and these varied from about 200 feet to 2,000 feet in length. The information reviewed included results from boring logs, Standard Penetration Tests (SPT), Cone Penetration Tests (CPT), soil classification testing, and shear strength testing.

2. The liquefaction potential of sandy and silty soils within both the levee and foundation soil strata was evaluated using the penetration test data and the well-established correlation developed by Seed, et al. (1984), with suitable corrections for magnitude and duration effects. Post-liquefaction shear strengths were evaluated based on the correlation developed by Seed and Harder (1990), and the performance of similar earth structures during recent earthquakes.

   Post-liquefaction shear strength estimates were used to evaluate the associated displacement and deformation potential of levees following liquefaction. The displacement or deformation evaluation was used to obtain an estimate of the potential for levee sections at each site to fail following an earthquake.

3. The resulting estimated levees failures due to liquefaction were then used to statistically characterize the likelihood of liquefaction-induced levee failures, for various levels of shaking, within each of the four Damage Potential Zones shown in Figure 4-1.

The evaluations outlined in these three steps were performed in both qualitative assessments as well as with quantitative approaches. Individual evaluations developed by sub-team members were resolved into a consensus ranges of fragility estimates. These estimates also incorporate differences in risk associated with daily (tidal) and seasonal variations in water levels in the rivers and sloughs.

The resulting liquefaction-related fragility estimates for each of the four Delta Damage Potential Zones are presented in Table 4-2. For peak accelerations less than 0.1g, the estimated fragility values are relatively low. This is in good agreement with the documented performance of Delta levees. Peak base accelerations have been estimated to be less than about 0.08g since reclamation of the Delta began in 1868 (see CDWR, 1992). As base accelerations (seismic loading) increase, the estimated levee fragility also increases for all four damage potential zones.

One of the important findings derived from the liquefaction fragility estimates is that the hazard associated with this mode of failure is much greater for Zone I (Sherman Island) than for the other three zones. This is because extensive layers of liquefiable sandy soils are known to exist within the levees protecting Sherman Island. No other levee is known to have such a large extent of liquefiable soil. In addition, Sherman Island is the western-most island, and is closest to the principal seismic source zones. Thus the island is most likely to experience strong shaking levels.

Another important finding is that for all four Damage Potential Zones, the fragility associated with potential soil liquefaction is much higher than that associated with potential non-liquefaction failure modes. This has important ramifications with regard to potential options for reducing seismic fragility along levee sections. Refer to Section 6 "Mitigation of Seismic Vulnerability".

TABLE 4-2: ESTIMATED FAILURE RATE (FRAGILITY) FOR BOTH LIQUEFIED AND NON-LIQUEFIED REACHES - FAILURES PER 100 MILES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damage Potential Zone	Levee Length (miles)	Estimated Fragility - Number of Levee Failures per 100 miles	
			Liquefied Reaches	Non-Liq. Reaches
0.05	I	20	0.005 - 0.50	0.030 - 0.075
	II	301	0.001 - 0.083	0.015 - 0.036
	III	116	0.001 - 0.033	0.003 - 0.010
	IV	223	0.001 - 0.033	0.003 - 0.010
0.10	I	20	0.20 - 2.5	0.050 - 0.12
	II	301	0.080 - 0.33	0.023 - 0.052
	III	116	0.050 - 0.15	0.004 - 0.017
	IV	223	0.050 - 0.15	0.004 - 0.016
0.15	I	20	2.5 - 10.	0.16 - 0.35
	II	301	0.66 - 1.7	0.070 - 0.15
	III	116	0.29 - 1.2	0.010 - 0.057
	IV	223	0.29 - 1.2	0.011 - 0.049
0.20	I	20	5. - 20.	0.36 - 0.77
	II	301	1.7 - 5.0	0.16 - 0.33
	III	116	0.88 - 2.3	0.022 - 0.13
	IV	223	0.88 - 2.3	0.025 - 0.11
0.30	I	20	15. - 30.	1.5 - 3.2
	II	301	5.0 - 10.	0.66 - 1.4
	III	116	2.4 - 5.9	0.092 - 0.53
	IV	223	2.4 - 5.9	0.11 - 0.46

4.6 ESTIMATES OF LEVEE FAILURES FOR NON-LIQUEFACTION EARTHQUAKE-INDUCED DISPLACEMENTS

Some marginally-stable levees will deform significantly during an earthquake due to cyclic inertial loading. Such deformations could lead to levee failure even if the levee and foundation soils did not experience liquefaction. Estimates of levee fragility for the non-liquefaction deformation mode of failure used the following approach:

- First, an estimate was made of the number of marginally stable levee sites in each Damage Potential Zone. Three levels of marginal stability were considered and the number of marginal sites for each level was estimated for each zone.

- The levee deformation that would be induced by earthquake shaking was estimated for each level of marginal stability using one-dimensional dynamic response analyses coupled with Newmark-type double-integration deformation calculations. The response analyses were used to develop estimates of deformation potential specifically appropriate to the usual foundation soil conditions prevalent throughout the Delta. Levee deformation estimates were generated for a range of base accelerations.

- The estimated levee deformations were then converted into probabilities of failure by considering daily and seasonal variations of channel water levels, varying freeboard, cracking, and seepage erosion and piping potential. The failure probabilities were then summed for each level of marginal stability within a zone, and then expressed as a levee fragility in terms of expected failures per 100 miles of levee within each zone for a range of base accelerations. These results are presented in the last two columns of Table 4-2.

4.7 ESTIMATES OF LEVEE FRAGILITY DURING SEISMIC EVENTS

Table 4-2 presents levee fragility values estimated for both liquefaction and non-liquefaction deformation modes of failure. In comparison with the liquefaction mode of failure, the non-liquefaction deformation levee fragility values are much lower, only approximately 10 percent of the liquefaction values. In addition, while there is a significant difference in the liquefaction fragilities estimated for Zones I and II, there is not as large a difference in the non-liquefaction deformation fragilities. This is principally because the number of marginally stable sites per levee mile are believed to be within the same order of magnitude within both Zones I and II in the central Delta.

4.8 MAGNITUDE CORRECTION FACTORS

The estimates for levee failures and fragility presented in Table 4-2 are for earthquake shaking associated with a magnitude 6.0 event. For the same level of shaking, larger magnitude earthquakes will induce more damage and more levee failures than smaller magnitude events because larger magnitude earthquakes have longer durations of strong shaking. To adjust the fragilities for earthquake magnitudes other than Magnitude 6.0, the following scaling factors were used:

A. Liquefaction Mode of Failure:

A magnitude correction factor for the liquefaction mode of failure was developed using the Idriss (1997) magnitude scaling factors for triggering of liquefaction. These corrections are slightly larger than those previously used by Seed, et al. (1984), and are slightly lower than those recommended by the NCEER Liquefaction Working Group (NCEER, 1997).

B. Non-Liquefaction Deformation Mode of Failure:

A magnitude correction factor for the non-liquefaction deformation mode of failure was developed using the Earthquake Severity Index described by Bureau et al. (1988). This correction is much larger than the one for liquefaction, but is comparable with the cyclic inertial deformation results obtained by Makdisi and Seed (1977).

Appendix B presents additional information regarding the estimates of the levee fragilities and the associated evaluations and calculations used to develop them.

5 PROBABILISTIC EVALUATION OF LEVEE FAILURES

5.1 METHODOLOGY

The seismic hazard analysis (or Probabilistic Seismicity Evaluation, as described in Section 3) was combined with the levee fragility evaluation to develop a probabilistic evaluation of the number of levee failures. The number of levee failures expected to occur in a single earthquake is a function of return period or annual likelihood of occurrence of different levels of earthquake intensity.

The levee failure probability analysis is an extension of standard probabilistic seismic hazard analysis. The difference is that instead of calculating the probability of the ground motion exceeding a specified value at a location, the probability of a specified number of levee failures being exceeded in a single earthquake was computed. In this way, the performance of the entire levee system was considered simultaneously. This avoids the problems of using individual site hazard curves, which may represent different earthquakes at different parts of the Delta.

These analyses consider the performance of the Delta levees for specific earthquake scenarios. For each earthquake scenario, the probability of one or more levee failures occurring within the Delta was computed. This process is repeated for two or more failures, three or more failures, and so on. Following the probabilistic seismic hazard analysis, rather than considering just one or two scenarios, all possible earthquake scenarios were considered and their probabilities of occurring were determined.

The probability of a given number of levee failures for an earthquake scenario is multiplied by the probability of the scenario earthquake actually occurring. This rate of failure is then summed over all of the scenarios to give the total rate of various numbers of levees failing in a single earthquake. A Poisson assumption for the earthquake occurrence is used to convert the rate of failures into a probability of failures. The result is a hazard curve for the "expected" number of levee failures in a single earthquake. The details of the mathematical formulation used in the probability calculation is described in Appendix C.

The resulting median hazard curves for levee failures are shown in Figure 5-1. Two curves are presented; one for the CRCV model and one for the without-CRCV model (see Section 3). The large difference for the two models reflects the impact of an assumed large CRCV blind thrust fault under the west end of the Delta. At low numbers of failures, the two source models lead to similar levee failure hazard because the hazard is controlled by large distant earthquakes on the Hayward and San Andreas fault and small local earthquakes. At larger numbers of failures, the differences between the two fault models become more pronounced.

The final, overall estimate of seismic levee fragility shown in Figure 5-2 was tempered by considering the uncertainties in the two fault models and the uncertainties inherent in the various elements of the overall seismic fragility and hazard evaluation. Thus, the fragility estimates include allowances for current sources of uncertainty with regard to both seismicity (loading) and seismic levee fragility (resistance).

The same Levee Fragility estimates are alternately shown with respect to return periods of 50, 100, and 200 years (see Figure 5-3). These graphs show the probability of exceeding a particular number of levee breaks in a single event during a given exposure time period.

5.2 ILLUSTRATIVE SCENARIO EVENTS

Three illustrative scenario earthquake events were developed to illustrate the potential for levee failures following a single earthquake:

1. Magnitude 7.1 earthquake on the Hayward Fault
2. Magnitude 6.25 earthquake on the Concord Fault
3. Magnitude 6.0 earthquake on the CRCV Fault, immediately northwest of Sherman Island

Figures 5-4 to 5-6 show the estimated number of levee breaks per zone and the peak acceleration contours for stiff soil or rock for each of these three scenario events.

As shown in Figure 5-4, a Magnitude 7.1 event on the relatively distant Hayward Fault produces low to moderate levels of acceleration of fair duration, and results in a low predicted number of levee failures (on the order of 0 to 4 failures throughout the Delta).

As shown in Figure 5-5, a Magnitude 6.25 Concord Fault event produces similar levels of peak acceleration at the western end of the Delta (on the order of 0.1g), but these rapidly decrease to the east. This, coupled with a relatively short duration, results in a lower level of predicted levee failures than for the Hayward fault event shown in Figure 5-4.

Figure 5-6 illustrates the third scenario event, a Magnitude 6.0 on the CRCV Fault at the northwestern edge of the Delta. The proximity of the fault rupture produces much higher levels of acceleration, and results in much higher predicted numbers of levee failures, especially in Zones I and II. The numbers of predicted failures for this scenario event are fairly high (on the order of 13 to 32 through the entire Delta), but the annual likelihood of occurrence of this even is much lower than for the events illustrated in Figures 5-4 and 5-5.

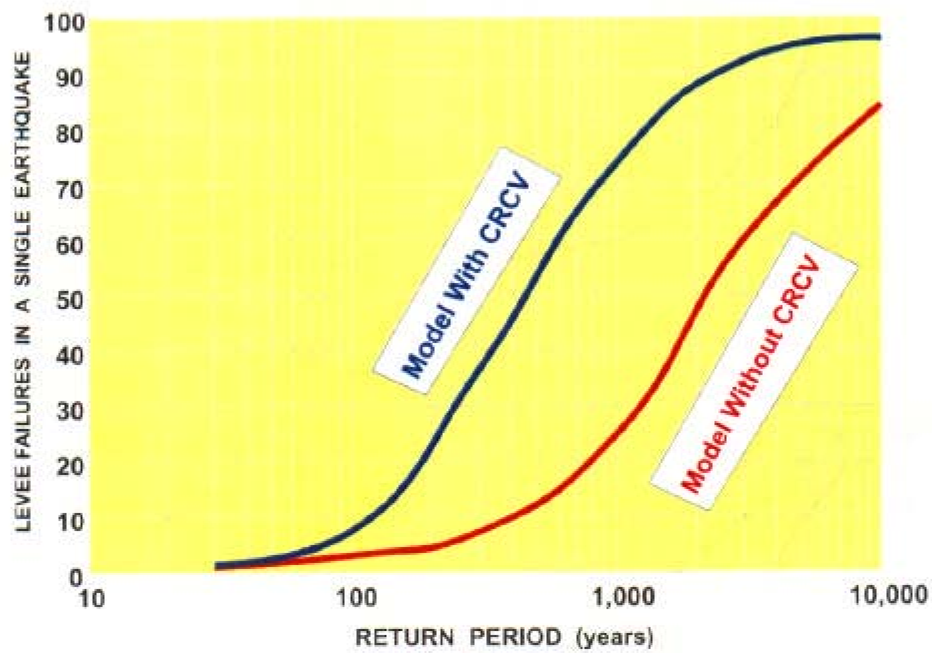

Figure 5-1: Number of Levee Failures in a Single Earthquake–both Fault Models Show

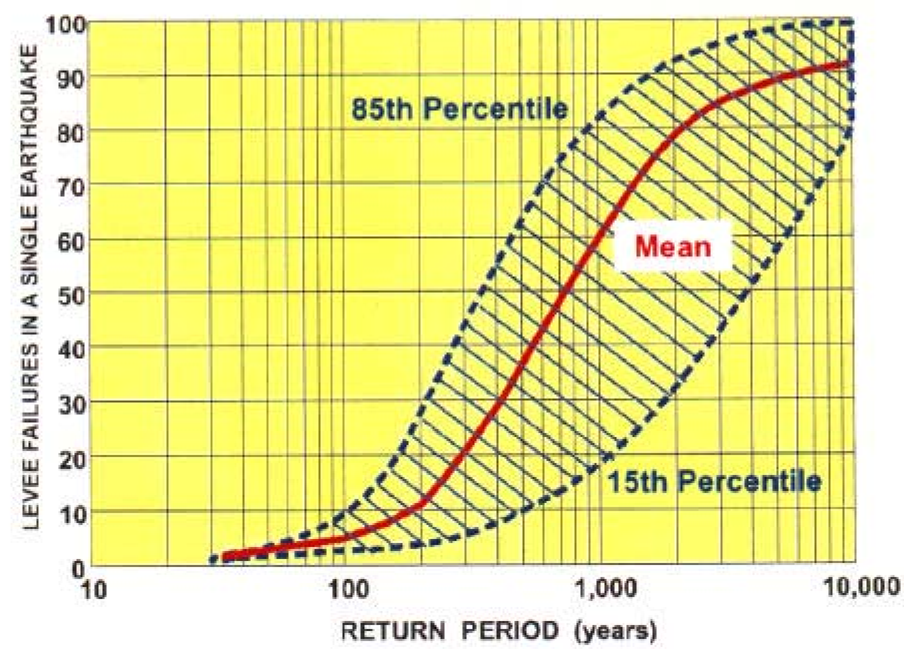

Figure 5-2: Number of Levee Failures in a Single Earthquake-Fault Models Combined
Note: Number of Levee Failures does not equate to Number of Islands Flooded

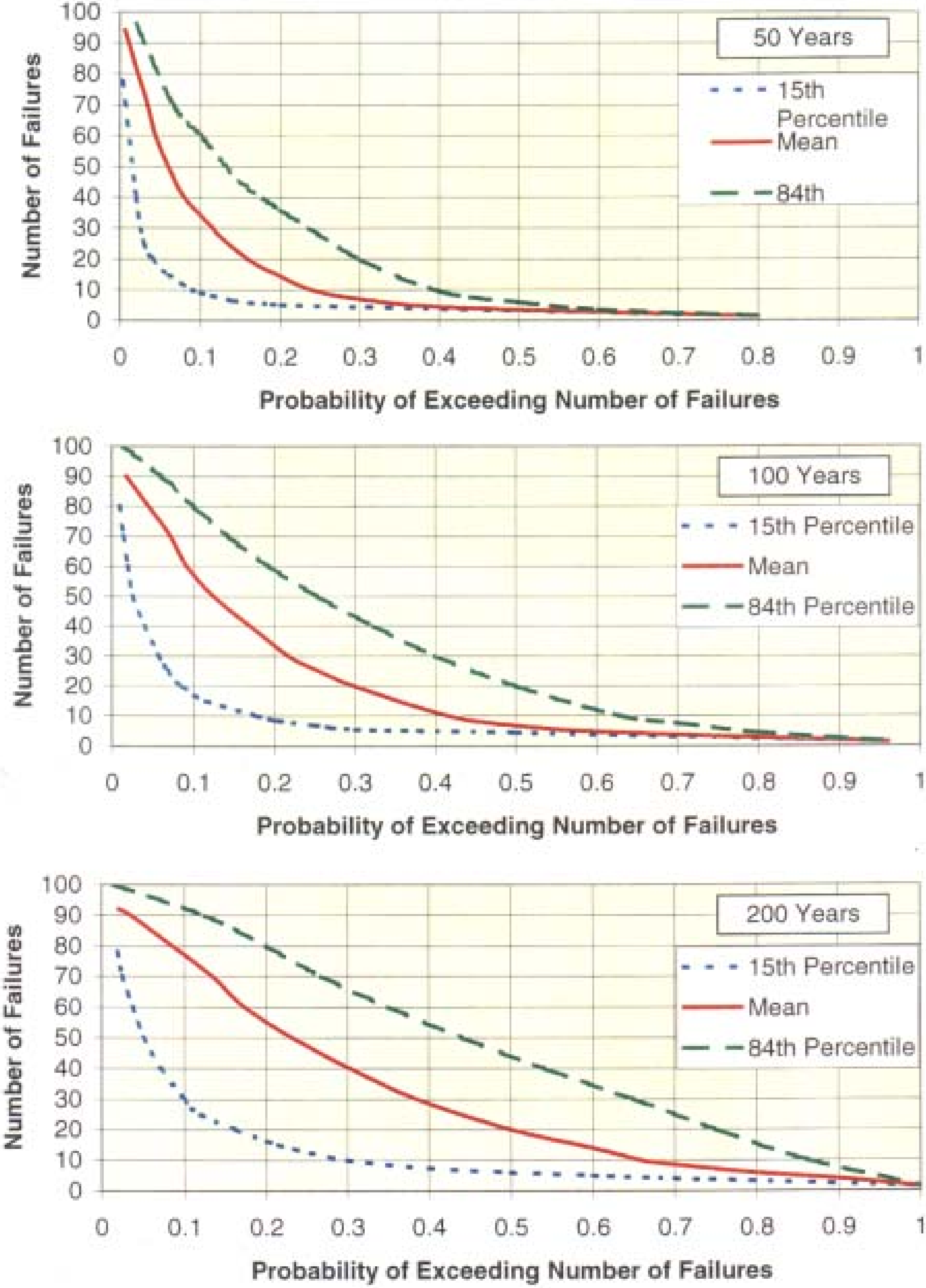

Figure 5-3: Probability of Exceedance vs. Number of Levee Failures for 50, 100 and 200 Year Return Periods

Note: Number of failures does not equate to numbers of islands flooded

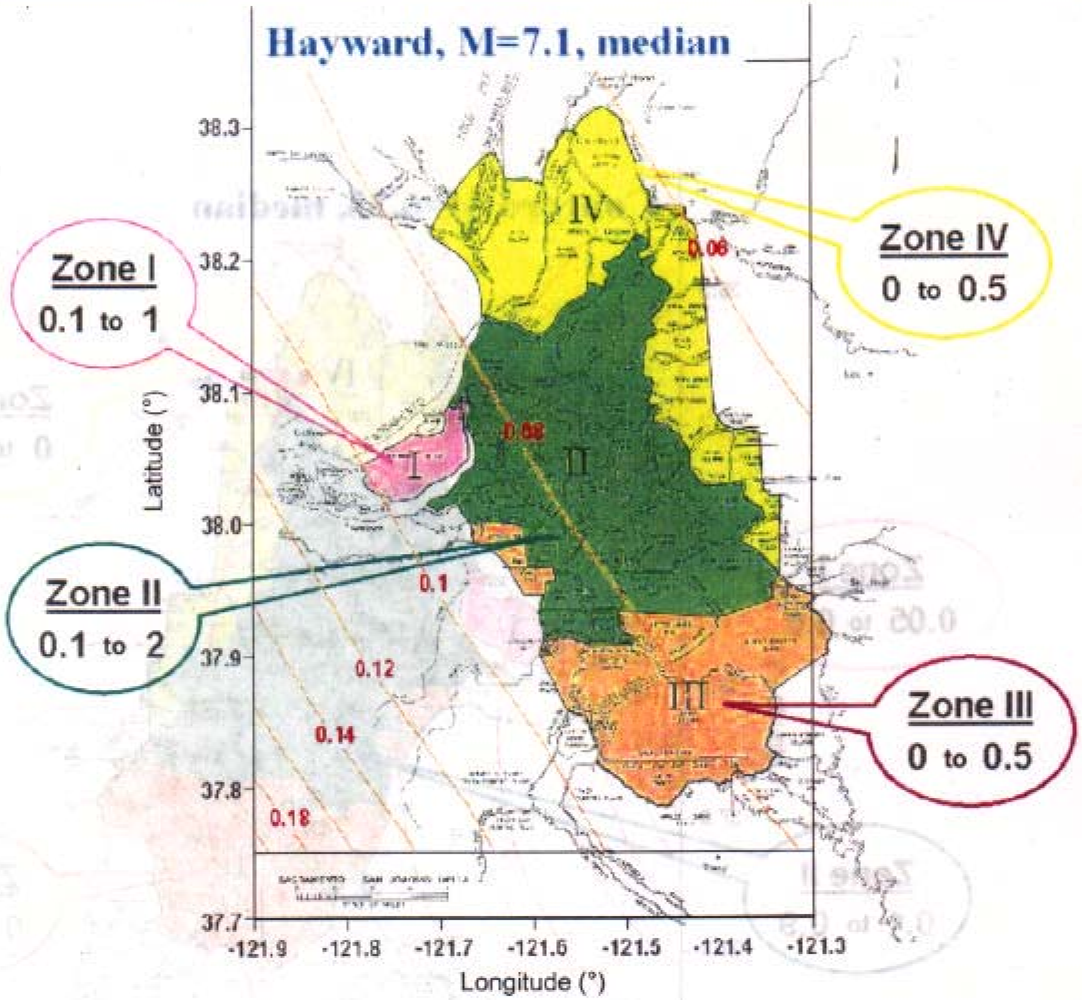

Figure 5-4: Expected Number of Levee Failures for a Magnitude 7.1 Earthquake on the Hayward Fault

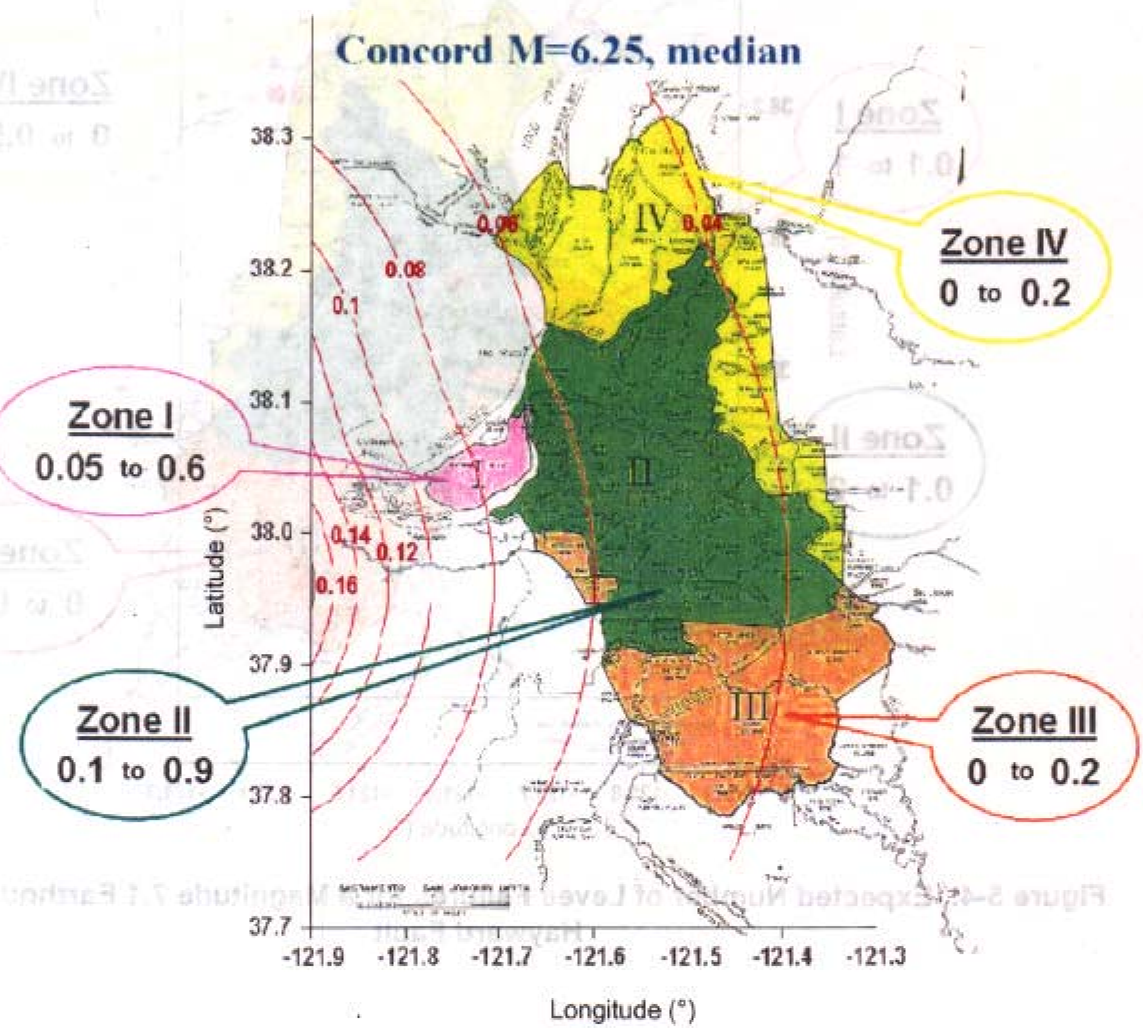

Figure 5-5: Expected Number of Levee Failures for a Magnitude 6.25 Earthquake on the Concord Fault

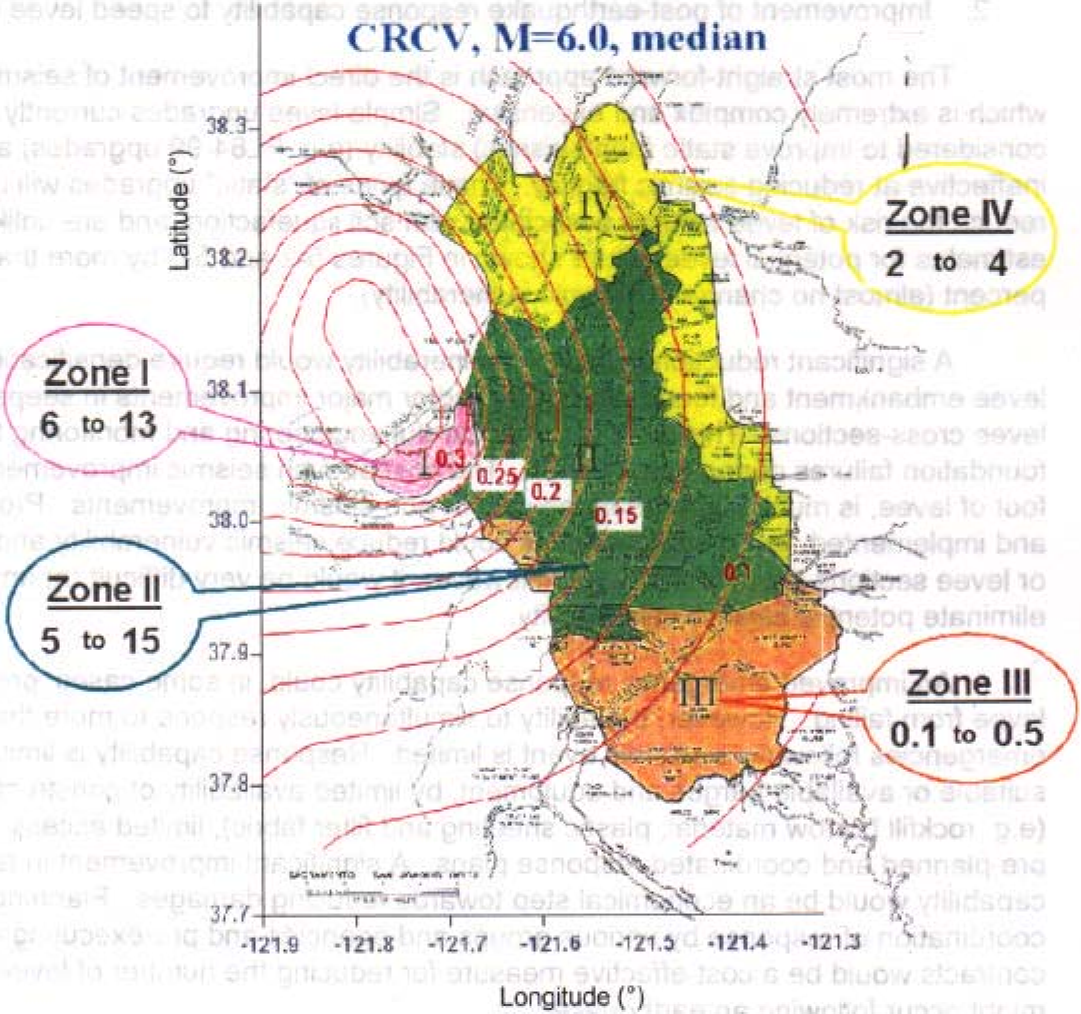

Figure 5-6: Expected Number of Levee Failures for a Magnitude 6.0 Earthquake on th CRCV Fault

6 MITIGATION OF SEISMIC LEVEE VULNERABILITY

There are several approaches which might be considered to reduce seismic levee vulnerability and its potential impacts. Two approaches are:

1. Improvement of seismic levee stability in order to directly reduce seismic vulnerability.

2. Improvement of post-earthquake response capability to speed levee repairs.

The most straight-forward approach is the direct improvement of seismic levee stability, which is extremely complex and expensive. Simple levee upgrades currently being considered to improve static (non-seismic) stability (e.g. PL84-99 upgrades) are largely ineffective at reducing seismic fragility. These types of "static" upgrades will do very little to reduce the risk of levee failures associated with soil liquefaction, and are unlikely to reduce the estimates for potential levee failure shown in Figures 5-2 and 5-3 by more than about 10 percent (almost no change in seismic vulnerability).

A significant reduction in seismic vulnerability would require densification of the loose levee embankment and foundation soils, and/or major improvements in seepage control and levee cross-sections. This work requires careful engineering and monitoring to avoid levee or foundation failures during construction. The cost of such seismic improvements, per linear foot of levee, is much higher than the cost of non-seismic improvements. Properly engineered and implemented, levee improvements could reduce seismic vulnerability and selected islands or levee sections could be targeted. However, it would be very difficult (at any cost) to fully eliminate potential seismic vulnerability.

An improved emergency response capability could, in some cases, prevent a damaged levee from failing. However, the ability to simultaneously respond to more than a few levee emergencies following a seismic event is limited. Response capability is limited by lack of suitable or available barges and equipment, by limited availability of construction materials (e.g. rockfill borrow material, plastic sheeting and filter fabric), limited access, and by a lack of pre-planned and coordinated response plans. A significant improvement in response capability would be an economical step towards reducing damages. Planning and coordination of response by various groups and agencies and pre-executing construction contracts would be a cost-effective measure for reducing the number of levee failures that might occur following an earthquake.

The development of seismically-protected water conveyance routes, either through the Delta or around the Delta, has been considered by others. Evaluating such alternatives was beyond the scope of the sub-team.

Similarly, it was beyond our scope to comment on expanding storage capacity south of the Delta.

7 SUMMARY OF FINDINGS

The studies presented in the previous sections were completed to provide an evaluation of the current seismic vulnerability of levees in the Sacramento-San Joaquin Delta. The major findings of this study are summarized as follows:

- Figures 3-1 and 3-2 show the principal faults considered in the development of a probabilistic assessment of seismicity. Two models were considered in this analysis: one includes a potentially significant blind thrust fault system along the western edge of the Delta, and the other one does not. Although both fault models predict about the same general levels of peak accelerations for a given return period (see Figures 3-3 and 3-4), the earthquake magnitudes associated with the motions are different, with somewhat higher magnitudes resulting from the CRCV fault model with the blind thrust fault.

- This study characterized the levee fragility of the Delta by subdividing the Delta into four Damage Potential Zones (see Figure 4-1). Seismic fragility is highest in Zone I, Sherman Island, due to poor levee embankment and foundation soils. Zone II, the central area of the Delta, has the next highest overall level of seismic levee fragility. Zones III and IV, with levees of lower heights and less saturated soil conditions, founded on generally firmer soils, have generally lower levels of levee fragility.

- Levee fragility within each of the four damage potential zones was estimated for a range of potential earthquake shaking. The two potential modes of levee failure used in this assessment were:

  (1) Soil liquefaction (loss of strength of saturated sandy and silty soils).

  (2) Inertially-driven deformations of "weak," marginally-stable levee sections.

  Levee fragility values for both of these potential modes of failure are presented in Table 4-2.

- Finally, seismic vulnerability was evaluated by combining the probabilistic assessment for various earthquake motions (loading) with the estimated seismic fragility (resistance) of different levee reaches. The fault model without the blind thrust fault gave lower predicted numbers of levee failures (see Figure 5-2: 3 vs. 7 levee failures in a single earthquake for a return period of 100-years). As it is not presently possible to conclusively select between the two faulting models studied, this study ended up averaging the results from the two fault models, with the final levee vulnerability results shown in Figures 5-2 and 5-3.

- A brief discussion of options for reducing the current Delta levee seismic vulnerability was presented in Section 6. It was concluded that attempting to significantly reduce seismic levee fragility will be both difficult and expensive, and that simply making relatively minor geometric modifications (e.g. along the lines of PL84-99 criteria) will not significantly reduce seismic vulnerability. Developing improved emergency response plans and measures (including stockpiling of critical materials and equipment) is thought to have considerable merit, especially in the short-term.

- The next phase of this committees' studies should include further examination of various proposed long-term mitigation alternatives and emergency response measures.